NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 252

THE DIRECT MEASUREMENT OF ENGINE POWER ON AN AIRPLANE IN FLIGHT WITH A HUB TYPE DYNAMOMETER

By W. D. GOVE and M. W. GREEN

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	sec	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/sec		horsepower	HP.
Speed		km/hr		mi./hr	M. P. H.
		m/sec		ft./sec	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight, $=mg$

g, Standard acceleration of gravity $=9.80665$ m/sec.$^2=32.1740$ ft./sec.^{2}

m, Mass, $=\frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} sec.^{2}) at 15° C and 760 mm $=0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m$^3=0.07651$ lb./ft.^{3}

mk^2, Moment of inertia (indicate axis of the radius of gyration, k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord length.

b/c, Aspect ratio.

f, Distance from $c.\ g.$ to elevator hinge.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force. (Note that these coefficients are twice as large as the old coefficients L_C, D_C.)

i_w Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting with reference to to thrust line.

γ, Dihedral angle.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, 0° C: 255,000 and at 15° C., 230,000;

or for a model of 10 cm chord 40 m/sec, corresponding numbers are 299,000 and 270,000.

C_p, Center of pressure coefficient (ratio of distance of $C.\ P.$ from leading edge to chord length).

β, Angle of stabilizer setting with reference to lower wing, $=(i_t-i_w)$.

α, Angle of attack.

ϵ, Angle of downwash.

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THE DIRECT MEASUREMENT OF ENGINE POWER ON AN AIRPLANE IN FLIGHT WITH A HUB TYPE DYNAMOMETER

By W. D. GOVE and M. W. GREEN
Langley Memorial Aeronautical Laboratory

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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REPORT No. 252

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By W. D. Gove and M. W. Green

SUMMARY

This report describes tests made at the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics to obtain direct measurements of engine power in flight. Tests were made with a Bendemann hub dynamometer installed on a modified DH-4 airplane, Liberty 12 engine, to determine the suitability of this apparatus.

This dynamometer unit, which was designed specially for use with a Liberty 12 engine, is a special propeller hub in which is incorporated a system of pistons and cylinders interposed between the propeller and the engine crankshaft. The torque and thrust forces are balanced by fluid pressures, which are recorded by instruments in the cockpit.

These tests have shown the suitability of this type of hub dynamometer for measurement of power in flight and for the determination of the torque and power coefficients of the propeller.

INTRODUCTION

A more complete knowledge of the power developed by airplane engines under the varying atmospheric conditions encountered during flight is of practical value in the development of aircraft. Indirect methods have been used in an effort to determine the variation of engine power with altitude. A common method is to use ground-level engine performance as a basis and to compute power by applying corrections for changes in temperature and pressure. Because of differences in volumetric efficiency, air fuel ratio, and mixture distribution the effect of altitude on the performance of aviation engines is somewhat variable. The correction of ground-level power of any one engine according to a general law is therefore only approximate. Power in flight can also be computed from propeller characteristics as determined from model propeller tests. This method is subject to errors resulting from indeterminate factors, such as the effect of fuselage interference and scale effect. A full-size propeller calibrated in place would furnish the data desired. It is obvious that more reliable information on any one engine could be expected from measurement of power under actual flight conditions.

Indicated horsepower has been measured by the Royal Aircraft Establishment at altitude by means of the R. A. E. electrical indicator. (Reference 1.) Conversion of I. HP. to B. HP. depends on a knowledge of the variation of the mechanical efficiency with density. An apparatus which measures directly torque in the crankshaft simplifies the determination of B. HP.

A hydraulic torque meter which was also arranged to measure thrust was developed by the D. V. L. (Deutsche Versuchsanstalt für Luftfahrt) laboratories in Germany before the close of the war. The apparatus was actually used in flight. (References 2 and 3.) Such a unit suitable for measuring the power of a Liberty engine was purchased by the United States Navy in 1924 and later used in these tests.

The suitability of this apparatus for flight test work was investigated while determining the variation in torque coefficient of the propeller with V/nD. Data were also obtained as to the variation in B. HP. of the engine with altitude. Since the apparatus measures tension in the crankshaft rather than effective thrust, the records of thrust were not considered.

DESCRIPTION OF APPARATUS

The Bendemann hub dynamometer consists of a special propeller hub in which is incorporated a set of small pistons and cylinders interposed between the engine shaft and the propeller in such a manner that the torque and thrust forces are balanced by fluid pressures in a closed hydraulic system. The fluid pressures so obtained, which are a measure of torque and thrust, are transmitted to suitable recording instruments in the cockpit. Since an apparatus of this type has not been used before in this country, a detailed description is given.

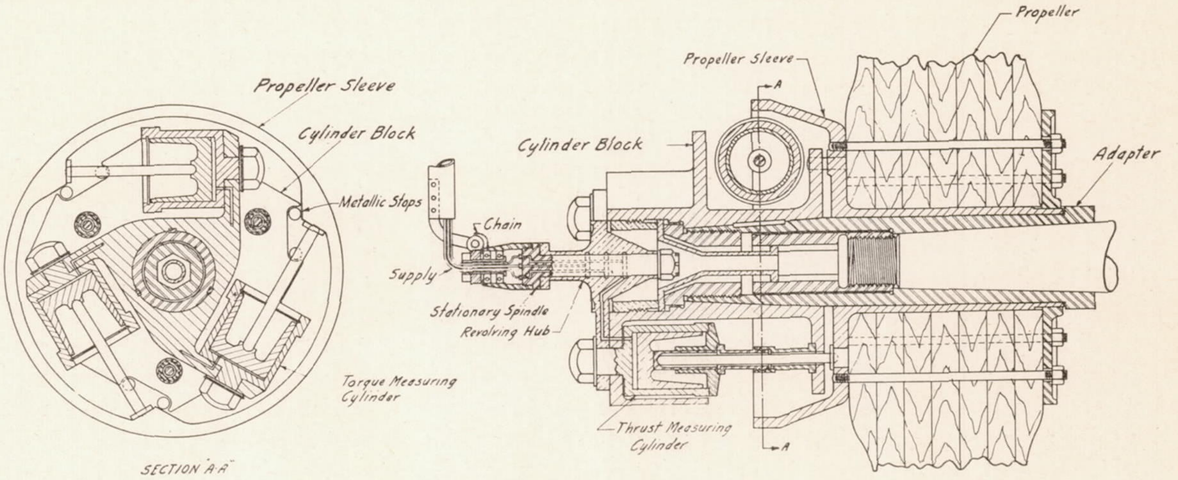

FIG. 1.—Sectional view of dynamometer hub

The dynamometer hub replaces the conventional propeller hub and allows the propeller to be mounted in its original position relative to the engine. The dynamometer mechanism is placed just ahead of the propeller, as shown in sectional views, Figure 1. It consists essentially of: (1) A steel sleeve adapter keyed to the engine crankshaft; (2) a cast-steel propeller sleeve which is a loose fit on the adapter; (3) a cast-steel cylinder block which is keyed to the adapter and contains the torque and thrust cylinders and drilled passages for transmitting working fluid to the cylinders; (4) a bronze spider and revolving hub containing drilled passages which register with the passages in the cylinder block to which it is bolted; and (5) a

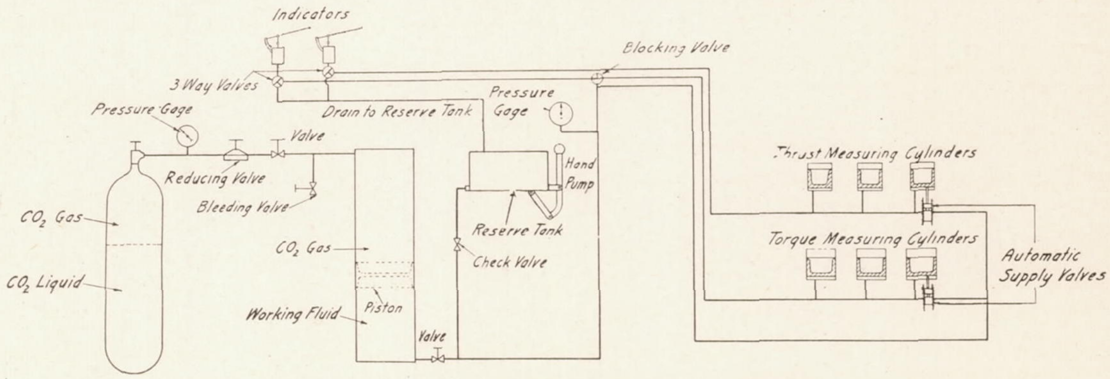

FIG. 2.—Diagrammatic sketch of Bendemann hub dynamometer

stationary spindle which contains drilled passages connecting with annular grooves in the revolving hub at one end and with tubes connecting the dynamometer hub with the recording instruments at the other end. The weight of the hub unit is 128 pounds.

The propeller sleeve is a running fit on the crankshaft adapter and is free to oscillate a few degrees and to slide axially a distance of one-eighth inch. Its rotational motion is limited by metal stops on the cylinder block and its axial travel is restricted by the rear shoulder on the

adapter and the cylinder block. The stops mentioned serve to drive the propeller in case of loss of liquid in the hydraulic system. Steel piston rods having hemispherical ends which rest in steel sockets at either end are interposed between the pistons in the cylinder block and the propeller sleeve and are of such length as to hold the propeller sleeve free of the stop lugs when the pistons are in working position.

The working fluid is introduced under all the pistons, and the fluid pressures generated in the cylinders by the torque and thrust forces are recorded.

Figure 2 gives a diagrammatic sketch of the complete dynamometer apparatus and shows the operation of the hydraulic system. A high-pressure supply of fluid is used to compensate for any leakage in the systems. Since each set of cylinders has connecting passages, admission of supply fluid is controlled by only one automatic valve on each set of three measuring pistons. Figures 3 and 3a show a torque-measuring piston and cylinder with the automatic supply valve.

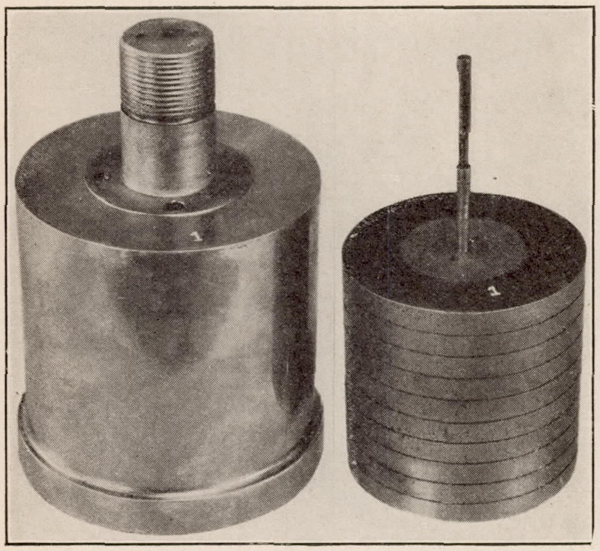

FIG. 3

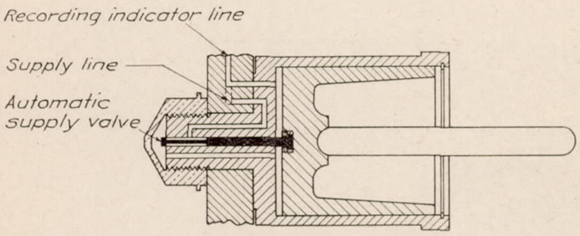

FIG. 3a.—Views and section of torque-measuring clyinder showing automatic supply valve

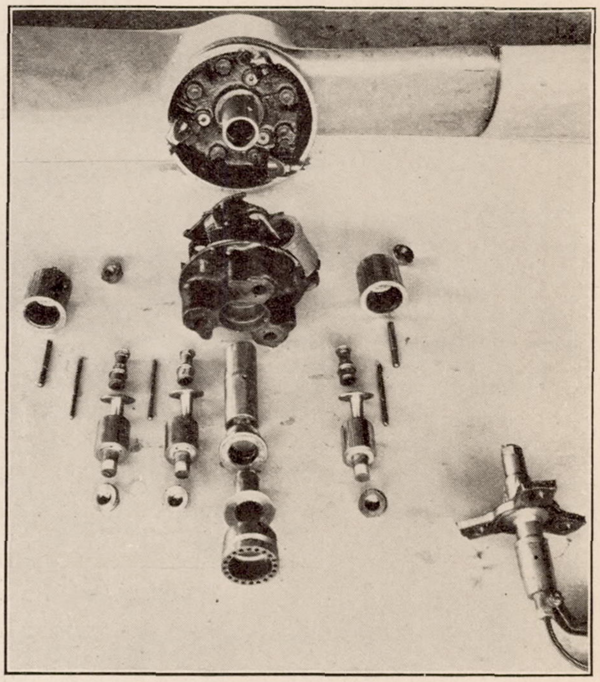

FIG. 4.—General view of hub parts

This valve is only opened when leakage causes the piston to approach the cylinder head and closes as soon as the fluid is replaced. This regulating valve is the outstanding feature of the dynamometer, and the regulation is adjusted to such a nicety that the motion of the piston is barely perceptible, and the indicator records do not show when the new fluid is admitted. Figure 4 shows the hub unit disassembled.

The rotating hub and the stationary tubing of the thrust, torque, and supply systems are connected as shown in Figure 1. The lines are connected to a stationary spindle whose radial holes register with annular grooves in the revolving hub. It is necessary to carry the tubing from the stationary spindle over the propeller to the controlling and recording apparatus in the cockpit. The torque and thrust lines lead to their respective recording instruments, each of which consists of a spring-loaded piston actuating an indicator arm carrying a brass stylus which traces a line on metallic-faced paper. A drum, revolved at constant speed by a clockwork, carries this paper. A third stylus traces a reference line.

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The supply line is served by a tank containing the working fluid. (See fig. 2.) Pressure in the supply tank is maintained by gas acting on a piston, the latter serving to separate the gas from the working fluid and to prevent absorption of the gas. A steel bottle partially filled with liquid carbon dioxide supplies the gas pressure, which is controlled by a regulating valve.

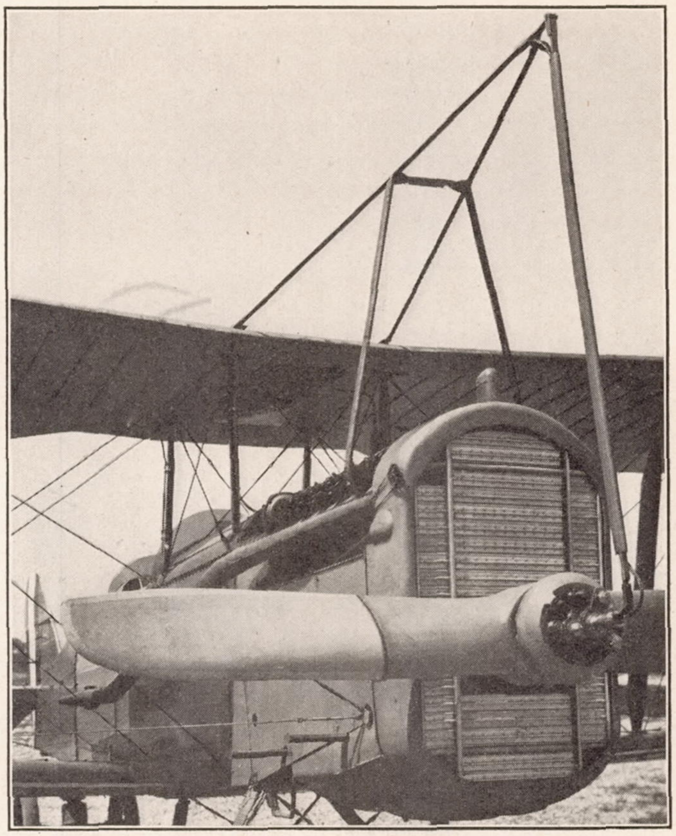

FIG. 5.—Installation in modified DH-4 airplane

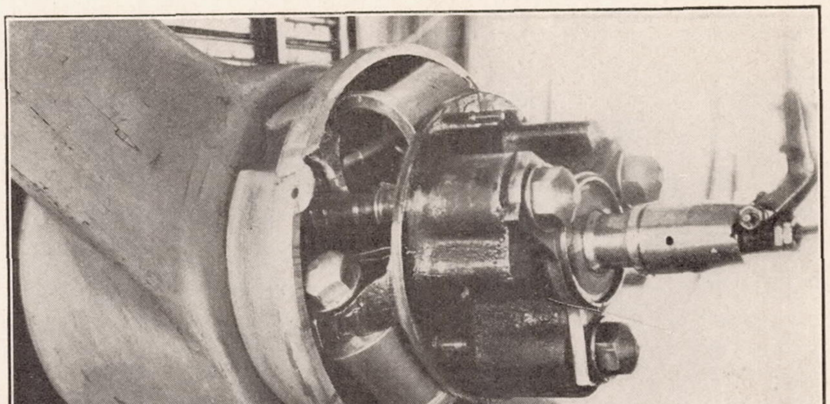

FIG. 6

The supply tank containing the working fluid can be replenished from a reserve tank by actuating a hand pump, fluid being pumped in under the piston. Pressure in the supply system is maintained at about 425 pounds per square inch, and the pressures in the torque and thrust systems never exceed 275 pounds per square inch.

Provision is made whereby the high supply pressure can be admitted to the torque-measuring cylinders, forcing the pistons out and locking the propeller sleeve against the metal stops. The propeller is locked in this way during glides or when the engine operates irregularly.

A typical installation is shown in a modified DH–4 airplane, Liberty 12 engine (figs. 5 and 6). It may be noted that there is considerable overhung weight at the propeller hub and that the tubing must be led around the propeller. Figure 7 shows the controlling and recording apparatus in the cockpit. The apparatus is quite bulky and requires considerable space.

In addition to the hub dynamometer, the following N. A. C. A. instruments were used during flight tests: Recording altimeter, recording air-speed meter, and automatic observer. (Reference 4.)

For measuring air speed a swivel-type Pitot static head mounted on the outer strut at a point about one-third the gap from the top wing was used. The automatic observer recorded

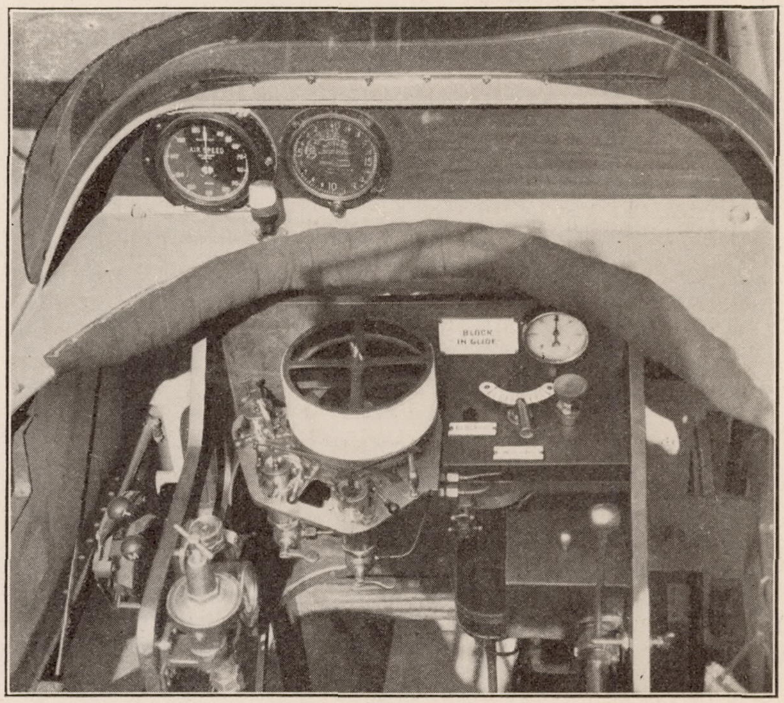

FIG. 7.—View of recording apparatus in cockpit

the air temperature from the indicator of an electric resistance thermometer. The engine speed was recorded by the automatic observer from a service-type tachometer. A distance-type thermometer was used to measure carburetor-air temperature, as it generally differs from the free-air temperature.

METHODS

PRELIMINARY TESTS

For preliminary test the dynamometer with a propeller was mounted on a portable test stand. Tests were made to determine the general operation and the nature of the further investigation required. It was found desirable to calibrate the apparatus in the laboratory against measured torque.

A fan brake was substituted for the propeller and the hub set up so that it would be driven by an electric dynamometer. The apparatus was then calibrated against the torque measurements of the electric dynamometer. In addition, static load calibrations of torque were made by holding the shaft rigid and applying known values of torque to the propeller sleeve.

A 2 to 1 mixture of glycerin and alcohol was selected as the most suitable working fluid, because it was sufficiently viscous to prevent excessive leakage around the pistons and its viscosity was least influenced by temperatures. A calibration of indicator deflection against measured torque was made with the 2 to 1 mixture of glycerin and ethyl alcohol. This curve is shown in Figure 8 with a computed curve which agrees closely with it. The computed curve was based on the dimensions of the dynamometer parts and unit pressures.

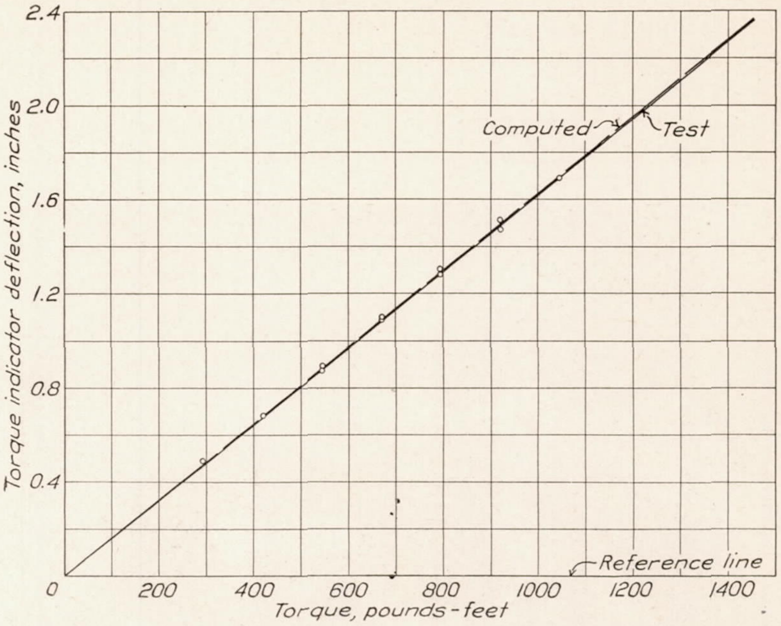

FIG. 8.—Calibration with 67 per cent glycerin and 33 per cent alcohol. Indicator deflection versus torque

FLIGHT TESTS

The flight tests were made for the dual purpose of obtaining data for the variation of torque coefficient of the propeller with V/nD and for the variation of full-throttle engine power with altitude. A series of full-throttle short climbs past a given altitude were made at various air speeds to cover a range of V/nD. The series was repeated at four altitude stations, the highest of which was 12,000 feet.

All records except those of the hub dynamometer were synchronized by timing lines. The dynamometer recording drum was always started at the same time as the other instruments, and since it turns at a known constant speed, it was easily synchronized with the other instruments.

DISCUSSION OF RESULTS

FLIGHT TESTS

Torque coefficients computed from data taken at the four altitude stations are plotted against V/nD in Figure 9. The torque coefficient determined was that given by the equation

$$C_q = \frac{Q}{\rho V^2 D^3},$$

where C_q is torque coefficient, Q is torque in pounds-feet, ρ is mass density of the air in pounds-feet-seconds, V is velocity of advance of the airplane in feet per second, D is diameter of the propeller in feet.

The points shown in the curve, Figure 9, represent data taken at different air densities. The fact that all points lie near an average curve demonstrates the practicability of calibrating a propeller at a convenient altitude with the hub dynamometer for the complete working range

of V/nD. A propeller calibrated by such a method would be particularly useful for measuring engine power at any altitude on supercharged engines, or on other tests where it is not practicable to use the hub dynamometer.

As the determination of the torque coefficient of the propeller is independent of engine operation, the variation of test points from the average curve of torque coefficient against V/nD was considered a reasonable basis for determining the precision of this method of measuring power. The maximum variation of the test points from the curve, Figure 9, is 4½ per cent.

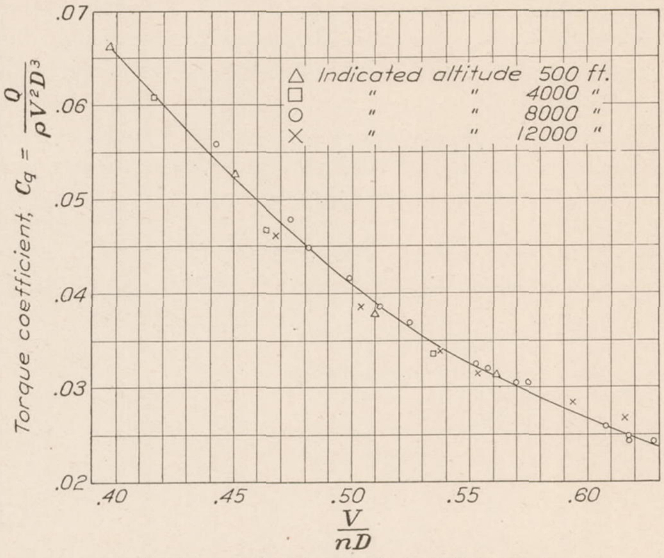

FIG. 9.—Torque coefficient versus V/nD. U. S. 12 propeller

This value includes errors in the measurement of R. P. M., air speed and density, as well as in the measurement of torque.

Figure 10 shows a curve of measured brake power against carburetor air density. All points represent full-throttle measured power at various engine speeds corrected by proportion to the mean speed of 1,650 R. P. M. It was considered best to plot power against carburetor air density, since the carburetor air temperature was always found to be higher than that of the surrounding air. Engine operation was not up to standard during the tests, due, it was found later, to the fact that there had been a leak in the ignition system.

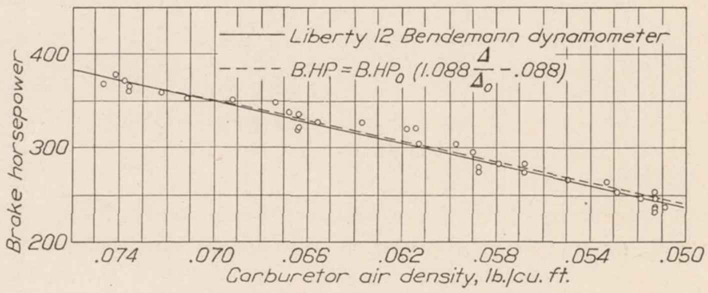

FIG. 10.—Brake horsepower versus carburetor air density

Although not conclusive, the results obtained on this one engine are indicative of the variation in power with density and represent data taken under actual operating conditions. The measured curve of power against density shown in Figure 10 agrees reasonably well with a curve computed from the relation

$$\text{B. HP.} = \text{B. HP.}_0 \left(1.088 \frac{\Delta}{\Delta_0} - .088\right),$$

where B. HP_0 and Δ_0 are respectively ground-level brake horsepower and density. This formula may be taken as representative of methods of computing power at altitude arrived at from theoretical considerations (Reference 5).

SUITABILITY OF BENDEMANN HUB DYNAMOMETER

Tests in the laboratory, using fluids of varying viscosity, show that the viscesity has little effect on the calibration of the hub dynamometer. Figure 11 shows calibrations made with a variety of working fluids, varying in viscosity from that of kerosene to that of castor oil. The total variation in calibration at 1,400 pounds-feet torque is 2.7 per cent. Any change in viscosity of the working fluid resulting from temperature changes encountered at moderate altitudes is well within the range of viscosities covered in these tests. The use of low-viscosity liquids, while not materially affecting the calibration, result in excessive leakage. The use of the apparatus is limited to moderate altitudes (15,000 to 20,000 feet), because any fluid of proper viscosity at ground level tends to solidify at the lower temperatures.

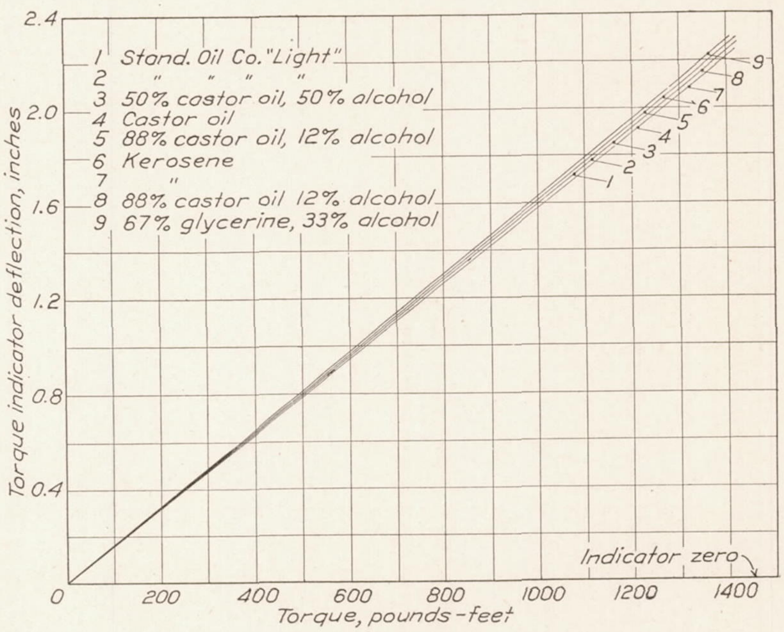

FIG. 11.—Calibrations with various working fluids. Indicator deflections versus torque

The general operation of the apparatus in flight was fairly satisfactory, with the exception that toward the end of the tests the dynamometer hub unit developed considerable vibration, which was attributed in part to the fact that the white-metal lining of the propeller sleeve on the adapter pounded loose and to the fact that the unit was found to be somewhat out of balance after the tests.

A very desirable improvement in the apparatus would be the elimination of the necessity for carrying the tubing around the propeller. This would eliminate any interference of the bracing around the propeller and its possible influence on propeller characteristics. A new design should also make the apparatus fully automatic.

The results of this investigation indicate that the Bendemann type hub dynamometer, with some limitations, is suitable for the measurement of engine power in flight for a moderate range of altitude.

CONCLUSION

The Bendemann type of hub dynamometer can be used successfully to determine the variation of the torque coefficient of the propeller with V/nD. As the torque coefficient for any one value of V/nD is constant regardless of altitude, a propeller calibrated by the hub

dynamometer is then made available for measuring power on tests where it is not practical to carry the dynamometer unit. The feature is especially applicable to the measurement of power on supercharged engines.

Engine operation at full throttle was not completely satisfactory during this investigation, but the incidental information concerning the variation of engine power with density conforms closely to that obtained from the equation

$$\text{B. HP.} = \text{B. HP.}_0 \left(1.088 \frac{\Delta}{\Delta_0} - .088\right). \quad \text{(Reference 5.)}$$

It is recommended that further flight research be undertaken to obtain additional and reliable information regarding the variation in brake power with density.

Experience with the present design has shown that it could be improved by reducing the weight of the hub unit, by making the apparatus fully automatic in operation, and by eliminating the necessity for carrying the tubing around the propeller.

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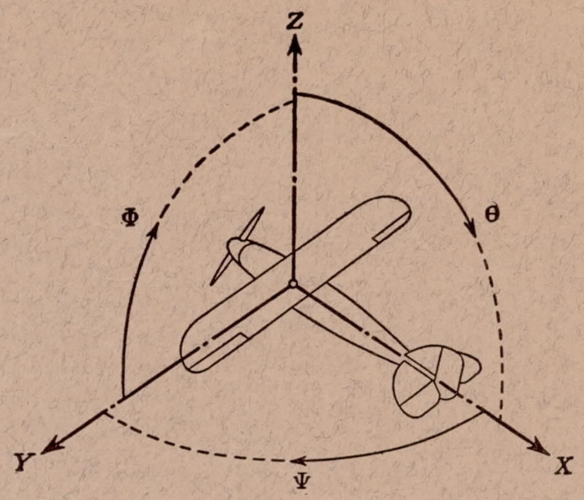

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	Φ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	Θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	Ψ	w	r

Absolute coefficients of moment

$$C_L=\frac{L}{qbS}\quad C_M=\frac{M}{qcS}\quad C_N=\frac{N}{qfS}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter.
p_e, Effective pitch
p_g, Mean geometric pitch.
p_s, Standard pitch.
p_v, Zero thrust.
p_a, Zero torque.
p/D, Pitch ratio.
V', Inflow velocity.
V_s, Slip stream velocity.

T, Thrust.
Q, Torque.
P, Power.
(If "coefficients" are introduced all units used must be consistent.)
η, Efficiency $= T\,V/P$.
n, Revolutions per sec., r. p. s.
N, Revolutions per minute., R. P. M.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 HP = 76.04 kg/m/sec. = 550 lb./ft./sec.
1 kg/m/sec. = 0.01315 HP.
1 mi./hr. = 0.44704 m/sec.
1 m/sec. = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft